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# Optimizing AEGIS ship stationing for active theater missile defense

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# NAVAL POSTGRADUATE SCHOOL
## Monterey, California

## THESIS

OPTIMIZING AEGIS SHIP STATIONING
FOR ACTIVE THEATER MISSILE DEFENSE

by

Mark Raymond Rios

September 1993

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OPTIMIZING AEGIS SHIP STATIONING
FOR ACTIVE THEATER MISSILE DEFENSE


by


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Submitted in partial fulfillment of the
requirements for the degree of


MASTER OF SCIENCE IN OPERATIONS RESEARCH

from the

NAVAL POSTGRADUATE SCHOOL
September 1993

# ABSTRACT

This thesis utilizes Extended Air Defense Simulation(EADSIM), a government-owned computer model, to determine the optimum stationing of an AEGIS ship in an Anti-Theater Ballistic Missile(ATBM) role defending two cities. The conclusions stated depend upon the validity of that model. The AEGIS ship's command being unsure of enemy launch sites and target intentions, the geometrically worst-case enemy launch points against the cities were modeled. Numerous potential positions from which an AEGIS ship could actively defend the cities with its Surface-to-Air missiles were assessed by simulation. Those positions which appeared advantageous were additionally evaluated in order to obtain greater confidence in the results of the ship's defense from those assigned stations. In order to aid in visualization of the results, expected TBM hits on the cities, and raid attrition by the AEGIS ship, were displayed on scatter, three-dimensional surface, and contour plots, from which the optimal stationing area of the ship was indicated.

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## ACKNOWLEDGMENTS

## EXECUTIVE SUMMARY

*PROBLEM:* A recommendation for the advantageous positioning of an AEGIS ship to intercept Theater Ballistic Missile(TBM) threats in a given scenario is required by the decisionmaker and is the focus of this study.

The coalition's defense against SCUD missiles during Operation DESERT STORM was largely ineffective, and diverted resources originally intended for other combat missions. During that operation, thirty percent of the Allies' theater tactical aircraft assets was shifted from battlefield air interdiction missions to locating and attacking SCUD launch vehicles. In spite of this effort, there was not one confirmed destruction of a TBM launch vehicle by a tactical aircraft. In addition, post-war analysis of the active TBM defense campaign by the PATRIOT missile system revealed that interception rates were far lower than those first claimed. This example strongly compels modern armed forces to develop systems and tactics capable of effectively countering the TBM threat.

Not only are theater ballistic missiles capable of delivering high-explosive warheads, but also nuclear, biological, and chemical weapons, termed "weapons of mass destruction". With potential adversaries having this pernicious capability, a system and tactics must be in place to defeat all incoming TBM threats with high probability,

since sustaining even a small nuclear or biological hit on a city or military site is unacceptable. The Ballistic Missile Defense Organization(BMDO) has directed that Army and Navy adopt a two-tiered approach for the *active defense* mission. For the Navy, the *lower-tier* provides area protection of debarkation ports, coastal airfields, and expeditionary forces ashore. The intercepting weapon used in this phase should be a dual-purpose surface-to-air missile(SAM) able to engage TBMs and aircraft. The Navy is experimenting with the SM-2 Block IV A missile which is designed to meet those requirements.

The *upper-tier* missile will give the defender a long-range exo-atmospheric capability against TBMs. This will protect military forces, critical assets and population centers. Intercepts at long-range and high altitude will minimize collateral damage of intercept debris on the ground and provide a greater defended area footprint. With technical development, testing, and evaluation well underway and heavily funded by Congress, an equally important concern is <u>where</u> to place AEGIS ships to best defend critical areas and objectives.

**SOLUTION METHODOLOGY:** This thesis addresses only the active defense pillar of Theater Missile Defense(TMD) through the use and positioning of an AEGIS ship for sea-based theater missile defense of two industrial cities in Southern Italy

from Libyan TBM strikes. An AEGIS ship with an upper and lower-tier surface-to-air missile capability in countering a raid of ground-launched 1500 km range TBMs was modeled in Extended Air Defense Simulation(EADSIM). EADSIM is a medium-fidelity analytic simulation model of air and missile warfare, including TMD. By modeling the sea-based AEGIS sensor and the SAMs with expected lethal envelopes and probabilities of kill($P_k$), trials were conducted to simulate the effects of ship position for maximizing TBM intercepts in this scenario.

*SOLUTION:* After one initial trial with 61 ship positions that could defend both cities, 33 closely met the measure of effectiveness requirement of two or fewer TBMs impacting a city out of a 12-TBM strike with high probability. This smaller group of 33 was then subjected to the same attack scenario nine additional times in Monte Carlo trials to obtain a more accurate expected number and variance of TBM hits on the cities. From these trials it was estimated that *11 positions met the measure of effectiveness of two or less TBM impacts in either city with an estimated probability of 90-percent and higher*. The results were graphed in contour and three-dimensional scatter plots to enhance visualization of optimal ship positioning.

# I. INTRODUCTION

## A. PURPOSE OF THE STUDY

As a result of the Anti-Ballistic Missile Treaty of 1972 and *detente* with the Soviet Union, the U.S. scrapped all fielded ballistic missile interceptors. However the threat of the SCUD Theater Ballistic Missile(TBM) to coalition forces and Israel during OPERATION DESERT SHIELD/STORM compelled rapid in-theater changes to the U.S. Army's PATRIOT system. This provided the U.S. the capability of intercepting SCUDs in the terminal phase of flight. Although spectacular SCUD vs. PATRIOT duels were broadcast live during DESERT STORM, AEGIS ships in the Arabian(Persian) Gulf were tracking the TBMs from hundreds of miles away, but had no missile capable of intercepting those TBMs.[Ref. 1:p. 56] By changing only 76 lines of the 1.1 million lines of computer code in the AEGIS' AN/SPY-1 radar and Weapon Control System(WCS), the ships have gained the capability to track the TBMs.[Ref. 2:p. 3]

Surface-to-Air missile interceptors are being developed to be deployed in the late 1990's, and the process of procuring a Joint Army-Navy missile is ongoing. With technical development, testing, and evaluation well underway and heavily funded by Congress, an equally important concern is <u>where</u> to place these weapons platforms to best defend

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critical areas and objectives. Actively countering a TBM by properly stationing a capable AEGIS ship for a given scenario is the focus of this study.


B.  BACKGROUND

Coalition experience in Operation DESERT STORM in combatting the SCUD Theater Ballistic Missile(TBM) was ineffective and seriously jeopardized the cohesiveness of the coalition.  In spite of a well-conducted air campaign using a thoroughly compiled target list in complete air superiority, an estimated 90 SCUDs were launched against coalition forces in Saudi Arabia and at Israel.

To keep the Coalition together, thirty percent of the theater's allied tactical aircraft assets were shifted from battlefield air interdiction missions supporting the land campaign, to locating and attacking SCUD launch vehicles. Yet there was <u>not</u> <u>one</u> confirmed destruction of a TBM launch vehicle by a tactical aircraft.  Additionally, post-war analysis of the active TBM defense by the PATRIOT missile system revealed  interception rates far below what was first claimed.  Because of their shoddy construction and the modifications necessary to achieve an increased range, Iraqi SCUDs were unbalanced in their downward flight.  Their erratic, corkscrewing descent caused many TBMs to break into fragments and self-destruct, inadvertently confusing the ground radars.  Those that didn't break up were particularly

difficult to intercept due to their unintentionally effective, maneuvering, final flight path.

## C. HISTORY

Modern missile technology traces its roots back to the early days of gunpowder and incendiary weapons. The war rocket, a short-range artillery weapon, was developed shortly after the discovery of gunpowder in the 14th century. Militaries on the Indian subcontinent were using war rockets by the end of the 1300's. Over the next 400 years, their use spread among the Chinese, Indian, and Arab armies, military forces of the same nations that continue to develop these weapons at present.

Today's modern ballistic missiles are the descendants of the German V-1 and V-2 programs of World War II. During that war, the German Air Force fielded the V-1 missile. Launched from a catapult, it was the first of what are now termed "cruise missiles". Powered by a pulse jet, the V-1 had a range of about 240km(150 miles). The V-1 campaign started in June, 1944, against London and other major cities. Nazi Germany fired about 20,000 missiles against allied cities and military staging areas. Great Britain's Royal Air Force radar and the air defense system shot down approximately 4,000 V-1's.

In September, 1944, the German Army began using a newer, more formidable weapon, the V-2. The V-2 was a

single-stage, liquid-fueled ballistic missile equipped with an inertial guidance system.  This weapon was mobile and launched from railroad flatcars.  It carried a warhead of 750kg of high explosives and had a 50 percent greater range than the V-1(350km).  In approximately 3,200 firings no V-2's were ever intercepted in flight.  Even more disturbing, in spite of an aggressive allied campaign to destroy the dreaded missiles on the ground by bombing, there was never a confirmed kill of a V-1 or V-2 on the ground.[Ref. 3:p. 5] That WWII lesson foreshadowed DESERT STORM events.

Immediately after WWII, the US and USSR salvaged V-1 and V-2 missiles and gave refuge to their scientists and engineers for employment in US and USSR national programs. Though the cruise missile was abandoned in the US after the Regulus Missile Program  the USSR developed the STYX family of cruise missiles, which have proliferated in original, duplicate, and improved versions throughout the world. These were the first modern cruise missiles to be used in Post-WWII combat(Egypt against Israel, 1967).

The US and USSR used captured V-2s in the earliest phases of their own cruise and ballistic missile programs. A direct descendant of the original 1940's German design, the Soviet SCUD is the most-common ballistic missile in the world and has been identified in the weapons arsenals of at least 16 countries.

## D. CURRENT THREAT

Currently, more than 20 countries have ballistic missiles. According to intelligence projections, nearly 40 will acquire or produce their own missiles by the end of the decade. The majority of the missiles are relatively short-ranged (120-600km), but, considering the geographic constraints, 300-500km is sufficient range to influence and damage cities and military targets in the Third World.[Ref. 4:p. 65] Countries such as North Korea, Argentina, and China could soon be producing missiles in the 1500-3000km range.[Ref. 5:p. 53] There have been some reports of an Iraqi "Al-Abed" system which has traveled over 1900km(1200 miles).

Beyond increasing missile ranges, the additional threat of improved guidance systems using the US's Global Positioning System(GPS) or the former Soviet Union's GLONASS is disquieting. Incorporation of such technology could bring much improved tactical accuracy to a presently inaccurate(SCUD Circular Error Probable is approximately 1000 yards) weapon. Most distressing to the major powers is the increasing availability of nuclear, chemical, and biological warheads. Grouped together in a category termed "Weapons of Mass Destruction(WMD)", these warheads mated with long-range TBMs would give Third-World countries strategic dominance in their regions. This capability in the hands of potential adversaries demands a weapon system

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and tactics development effort focused on defeat of all
incoming TBM threats with high probability.  The
consequences of sustaining even a small nuclear or
biological hit on a city or military site is unacceptable.

### E. OPTIONS TO COUNTER THE THREAT

There are various methods and options to defend against
the Theater Ballistic Missile threat.  These are defined by
the Joint Chief of Staff in the TMD Mission Need Statement
as "The Four Pillars of TMD".  These are:

Passive Defense: enhancement of the survivability of
friendly forces and assets.

Battle Management/Command, Control, Communications and
Intelligence(BM/C3I): effective communications, command
and control of TMD operations and data flow.

Attack Operations(Counterforce): destruction of the
enemy's capability to launch missiles.

Active Defense: intercepting the TBM in flight so as to
destroy the ballistic missile and negate the warhead.

### 1. Counterforce

The first two pillars of defense are a part of any
modern military operation.  However, the last two pillars
require further explanation.  The Counterforce option has
three windows of opportunity.

The first is the fixed infrastructure where the
missiles, warheads, and transporter erector launchers(TELs)
are designed, produced, and stored.  The second is the
forward support logistics infrastructure where the enemy

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moves his TBM systems prior to hostilities. Last is the launch phase, when the missile and warhead on the TEL are moved to the firing point and launched. After the poor showing by coalition forces in the SCUD-hunting campaign, there has been a renewed emphasis on attempting to improve counterforce capability through better sensors, weapons, and BM/C3I.

The Counterforce option is very difficult. Tactical camouflage and concealment, combined with the mobility and size of the TELs, makes finding the TBMs before launch challenging. Regardless of those challenges, destroying WMDs before launch in the counterforce phase is the most highly desired option and will net the greatest payoff. But when viewed historically, it will probably not achieve the expected attrition rates of a well-structured active defense. Rather, it complements the active defense option by restraining enemy launch plans and compelling the enemy to launch hurriedly, thereby degrading his launch efforts and his ability to conduct a successful attack.

### 2. Active Defense

Since the trajectory of a ballistic missile can be divided into three phases, there are also three windows of opportunity in Active Defense: *boost and post-boost*, *midcourse*, and *terminal*.

The boost phase refers to the early portion of missile flight, when the missile booster engine burns and thrusts

the vehicle to terminal velocity.  The rocket motor burns for about 10 to 20 percent of the TBM's total flight time. The post-boost phase is the period immediately after booster engine burnout, which initiates the release of the TBM's warhead(s) into the exo-atmosphere, perhaps 100km above the earth's surface.  The midcourse phase refers to the relatively long period when warheads coast along their ballistic paths.  The terminal phase is the final portion of the flight, when the warheads re-enter the atmosphere and proceed downward to their intended targets.

Each phase of a TBM's flight represents a unique interception opportunity.  Boost Phase Intercept(BPI) has the greatest benefit since the missile is destroyed early in its flight before multiple warheads and decoys can be expelled.  Additionally, TBMs intercepted in the boost phase fall on enemy-held land, which is especially important should WMDs be used.  Logically, the TBM is still connected to its booster rocket and thus is large, bright, slow-moving, and therefore relatively easy to kill in this phase. Attrition in this phase means fewer TBMs must be intercepted down range in proximity to the defended area.

BPI is difficult because it requires considerable sensor capability to acquire the TBMs.  The short time span from TBM launch to the end of the boost phase, perhaps only as long as 80 seconds, mandates that the interceptor be nearly over the enemy, or be capable of reaching the

boosting TBM extremely quickly. Currently the U.S. Air Force is conducting research and analysis on Boost Phase Intercept in ATBM defense. Ideas being considered are ultra-high altitude manned, or possibly unmanned, aircraft with laser-like weapons. This was the ideal regime in which spaced-based sensors and weapons("Brilliant Eyes/Pebbles") were designed. However, with the considerable reduction of the Soviet threat and a shrinking defense budget, the present administration has decreed that there will be no weapons in space.

In the midcourse phase of its flight, the TBM follows a ballistic path. Intercepts during this phase will be at very high altitudes and at long ranges from the TBM's target, thus tending to reduce collateral damage. In this extremely high altitude environment, infrared detection and guidance are very promising. During this phase of the TBM's flight, however, decoys or penetration aids("penaids") are dispensed, adding to the defender's problem of target selection.

There are advantages to intercepting the TBM in the terminal phase. Upon reentering the atmosphere, actual warheads are better discriminated from decoy penaids. Defense against TBMs in their terminal phase of flight can also be consolidated with conventional air defense. Most significantly, there is already a capability in this intercept phase today. The challenges are that the

decelerating TBM may intentionally(or by poor design,
unintentionally) maneuver, leaving limited interceptor
engagement time before TBM ground impact. Even if
successfully engaged, the TBM may scatter debris over the
defended area, causing serious collateral damage.

The Ballistic Missile Defense Organization(BMDO)
directed that the Army and Navy examine the active defense
mission through a two-tiered approach. For the Navy, the
lower-tier weapon provides area protection of debarkation
ports, coastal airfields, and expeditionary forces ashore.
The Army's upgraded PATRIOT system provides an example of
this baseline proficiency. The intercepting weapon used in
this phase should be a dual-purpose surface-to-air
missile(SAM) able to engage TBMs and aircraft. The Navy
plans fielding the SM-2 Block IV A missile in 1998 to meet
these requirements.

The upper-tier missile will give the defender a long-
range exo-atmospheric ability against TBMs to protect
military forces, critical assets, and population centers.
Intercepts at long range and high altitude will minimize
collateral damage on the ground and provide a greater
defended area footprint. While the Army is developing the
Theater High-Altitude Area Defense(THAAD) system, the Navy
is pursuing a Lightweight Exo-atmospheric Projectile(LEAP).
Under constrained funding, only one of the systems will
likely be selected for procurement. In combination with the

lower-tier weapons, the anticipated synergism of the systems will allow multiple interception possibilities, providing defense-in-depth from TBMs.

To summarize, TBMs cannot be countered by merely one simple technical solution(PATRIOT, AEGIS, Corps SAM, BPI...), but must employ a mixture of these capabilities. Closely coordinated joint and combined efforts using existing and future systems will be necessary to provide adequate defense. The best answer is a balance of effective attack operations, comprehensive active operations, practical passive defenses, and a robust C3I and surveillance capability. Lastly, the US should be able to include allied cooperation into this effort, since the outlook is that coalition warfare will be encouraged in future military actions.

# II. NATURE OF THE PROBLEM

## A. PROBLEM DEFINITION

In this section a specific problem concerning the defense against TBM attack of a vital objective(an allied nation's cities) is addressed. An AEGIS ship is to be positioned in an advantageous(optimal) way so as to counter an enemy long-range TBM attack on two strategic cities.

The study methodology is computer simulation using Extended Air Defense Simulation(EADSIM). The simulation results will be analyzed using statistical techniques and presented in response surface methodology. The objective is to station a single AEGIS(Anti-TBM) ship to minimize the chance of a TBM missile targeted at one of the cities from penetrating the defense.

## B. DESCRIPTION OF A HYPOTHETICAL PROBLEM

The United States and her NATO allies are greatly concerned with the threat of ballistic missile launches from Libya. Long-range TBMs launched from sites in that country can strike several cities in Europe. This scenario also

features a long overwater flight, and thus is appropriate
and timely for this study. Figure 1 depicts possible flight
paths.



**FIGURE 1.** Geography of Example TBM Scenario

## C. SCENARIO DESCRIPTION

To avenge the loss of face suffered during the Reagan-
Bush years and Western military raids on its State-sponsored
terrorist training camps in the desert, Libya can be

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expected to fire advanced, Russian-built TBM's, which have been modified for greater range, at targets in Europe.  In this study the targets are presumed to be the populous industrial Italian cities of Rome and Naples.

The attacks will originate from two separate launch sites, the locations of which are unknown to allied forces. Should a TBM launch occur, the TBM flight path can be "backplotted" accurately to its area of origin through a combination of sensors.  The sites can then be counter-targeted in an attempt to destroy the launch vehicles, thus reducing future launches.

### 1. Enemy Capabilities

Libya has procured, from a previously Soviet-supplied country, a transportable theater ballistic missile with a range of 1500 km.  Known as the "Al Kaddafi", the missile has a 500 kg warhead and has the potential to be a weapon of mass destruction(WMD).  The missile is launched from a Transporter Erector Launcher(TEL).  The TEL can transport a TBM on paved and graded dirt roads and can remain untargetable in "hide sites" until just before use. Locating mobile TBM launching systems before hostilities begin is exceedingly difficult.  Only 45 minutes are required for launch preparation and ten minutes are needed to get the launcher underway after firing.  Libya intends to use this system as a terrorist weapon to compel Western

governments to cease violating Libyan borders, presumably in defense of their own national security.

The Libyans have a capable air force by third world standards. But it would be foolish to send a manned air strike over 1000km to attack a Western European nation. Even a well-planned strike would give the defending country adequate time to intercept and engage the attack with aircraft and SAMs. Because of flight path and speed, a TBM raid allows for little warning time, and countering the raid is very challenging.

The Libyans have utilized TBMs before. In 1986, they fired TBMs at US forces on the island of Lampedusa in the Sicilian Straits in response to US air strikes on Libyan targets. Although the missiles impacted the island they missed their mark, but the attack signalled a new threat with which to contend.

Using Iraqi TBM operations in the Gulf War as a reference, it is expected that the Libyan attack will consist of 12 TBMs in a raid, since the Libyan's have only 12 launch vehicles. The 12-TBM raid will consist of six missiles fired at each of the target cities, Rome and Naples. This firing scheme might produce more TBM hits since the defenders must spread out their resources. Iraqi firings were observed to be scattered between one and six minutes apart. In the scenario to be studied here, the Libyan firings occur every 30 seconds because of better

command and control and also to make the scenario more
challenging for the ship.

## 2. Friendly capabilities

Suppose an AEGIS ship capable of intercepting TBMs is
stationed in the Central Mediterranean. With spaced-based
cueing it is expected to get a first detection of the
inbound TBM at approximately 400 miles from the ship and
missile intercept at 250 miles with the upper-tier weapon.
The upper-tier weapon is designed solely for use against
TBMs; therefore it is built to operate in altitudes between
100,000 and 250,000 feet. Flying in the exo-atmosphere, it
has an average velocity of 2000 meters/sec, and has a
single-shot probability of kill against a TBM of
$0.75(P_{ssk}=0.75)$.

The ship is also armed with a dual-purpose anti-
aircraft and anti-TBM missile. This weapon's altitude
ceiling is 100,000 feet and its range is much less than that
of the upper-tier weapon. It is slower than the upper-tier
weapon, flying at approximately Mach 3(800 meters/sec), and
also has a single-shot probability of kill of 0.75 against
TBM targets.

It is standard doctrine to shoot a salvo of two
missiles per target and evaluate the firing success after
the predicted intercept to decide whether further firings
are required for a kill. As modeled, the ship can engage a
maximum of 18 targets simultaneously.

## D. PROBLEM ASSUMPTIONS

For the purposes of this study, the following realistic assumptions were made:

-The theater ballistic missile will have a typical flight profile of a 1500 kilometer range missile.

-A spaced-based sensor or high altitude aircraft will initially detect the launch of the ballistic missile and provide a cue or alert of an expected track to the AEGIS ship.

-The AEGIS ship, on high alert status in an operating area at sea, will receive the track information from the sensor and have the AN/SPY-1 radar prepared for the earliest possible detection of the missile.

-Should a hit be achieved by the ship-launched missile, the TBM will be deemed destroyed or killed.

-However, if the TBM is not intercepted in its flight, it has a 100 percent probability of hit($P_h$=1.0) against its intended target, modeling the worst case situation.

-The AEGIS ship will not be threatened by any other air, surface, or sub-surface platforms.

-It is reasonable to assume that night or adverse weather has no effect on either forces' operations.

-All participants modeled are operating at complete combat readiness and no mission area degradations.

-No TBM decoys are used by the Libyan forces.

-No jamming is used to counter US air defense.

-No terminal maneuvers will be conducted by the TBMs to evade intercepting SAMs.


Though single ship employment is probably realistic in this geographic and political scenario, other creative situations in littoral waters and maritime chokepoints against stronger countries could seriously challenge a single ship or Surface Action Group.

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## E. MEASURE OF EFFECTIVENESS

Since no flawless defense system exists, it must be accepted that some TBMs will penetrate the AEGIS TBM engagement zone. It is presumed that each of the cities can absorb at most two hits. This presumption is based on the political ramifications of the missile strikes and the belief that disaster response activities could respond to two impact sites in each city. The TBM hits on the cities would seriously damage structures and start intense fires on the ground from the residual rocket fuel. *A ship position which would allow only two or fewer missiles to impact on a city with high probability is the measure of effectiveness.*

# III. METHODOLOGY

The mobile sea-based AEGIS weapon system will be
modeled with expected engagement volumes and probabilities
of kill($P_k$). Trials will be conducted to simulate the
effects of various explanatory factors for TBM intercept in
this scenario. This scenario will be modeled using EXTENDED
AIR DEFENSE SIMULATION(EADSIM), Version 2.07.

## A. SIMULATION DESCRIPTION

EADSIM is an analytic, attack/response simulation model
of air and missile warfare. It is a mid-fidelity force-on-
force analytic model developed by Teledyne Brown
Engineering. It has been used primarily by the U.S. Army's
Space and Strategic Defense Command and Missile Command as a
low-cost, high-repetition, interim analysis capability to
evaluate architectures for improving current air defenses,
include Theater Missile Defense.[1] Each platform, e.g., a
fighter aircraft, is individually modeled, as are the
interactions among the other platforms. The simulation
models the Command and Control(C2) decision processes and

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[1]For a complete description of the simulation, refer to:
*Extended Air Defense Simulation Methodology Manual*, Teledyne
Brown Engineering, Huntsville, AL, April, 1992.

the communications among the platforms on a message-by-message basis.

## 1. Model Configuration

The full analytic configuration of the model consists of four processes:

-Command, Control, Communications, and Intelligence(C3I)

-Flight Processing

-Detection

-Propagation

The C3I process is the core of the model. It performs the C2 decision and track processing, in addition to the engagement and weapons modeling for all the platforms in the scenario. Flight Processing controls the movement and status of each air platform. The Detection Process models each sensor in the scenario and determines when detection of a platform by another platform's sensor occurs. The Propagation process controls communication connectivity and message transfers. This process will not be used in this scenario because there is only one SAM site, the AEGIS ship.

The C3I process is the only one of the four run-time processes that is event-driven, rather than time step-driven. The C3I Process performs all the modeled battle management functions for each platform in the scenario. These functions are dependent upon the platform's mission and scenario environment.

Given the environment, specific rulesets are executed that determine the activities of the platform, including the allocation of weapons against targets. This process also performs engagement modeling for surface-to-air and surface-to-surface weapons.

Surface-to-air engagement modeling allows the platform: to search and identify targets, to choose the target most threatening to itself or to its assets to defend, and to assign a weapon to the threat to engage and destroy it. Semi-active, "fire-and-forget", and Non-Line of Sight missiles are modeled.

An engagement will be initiated when the target can be intercepted by one of the ship's SAMs. All of the SAMs are simplistically modeled as having a constant-velocity flight in a straight line to the intercept point. (For a more realistic simulation, a kinematically correct flyout profile of the missile could be loaded into the data base for usage. This would make the simulation model classified, and beyond the scope of this study.) When a SAM reaches its target, a "kill" or "no-kill" determination is made based on the $P_k$ assigned to the SAM against the target.

Surface-to-surface modeling provides for targets to be selected and engaged by TBMs and cruise missiles. Ballistic missiles are flown either in a depressed or a lofted trajectory profile. Normally, the kill assessment for the surface-to-surface weapon is a "kill" "no-kill"

determination made by random draws based on the user-defined $P_k$ values for a TBM against each a target. In this scenario, each TBM that survives its flight through the TBM engagement zone to its destination is deemed to be a success, since the worst-case situation is that WMDs are used in the warheads.

### 2. Rulesets

The ruleset under which the platform is operating determines its actions and behavior. Rulesets govern the response of the platform being threatened and its activities modeled in order to carry out its mission. There are a number of different rulesets in EADSIM: Flexible SAM, AWACS, Intelligence Fusion Post, Fighter, Airbase, etc. The AEGIS ship will be modeled using the Flexible SAM ruleset, which allows the ship to engage aircraft or air breathing threats(ABTs) and TBMs. There are four phases of the Flexible SAM ruleset in operation: Target Select, Launch, Intercept, and Reload.

#### a. Target Select Phase

The AEGIS ship must be actively tracking the TBM so that a threat assessment, weapon-to-target assignment, and launch queue construction can be performed. The TBM will be engaged only if it threatens the AEGIS ship or a pre-designated asset, e.g., a city, that the ship must defend. This is based upon the predicted impact point of the TBM. This step is performed on board the ship and uses

the predicted TBM trajectory for intercept calculations.
The AEGIS ship is able to distinguish between aircraft and
TBMs by observing user-specified minimum and final TBM
assessment altitudes and the rate of change in the
altitude(climb rate) which uniquely identify a TBM. In the
model, the impact point of the TBM cannot be determined
until the threat has reached its apogee and is descending.
The priority of the threat, relative to other threats, is
based on the shortest time until the threat's impact. Thus,
the TBM which would impact first would be the highest
priority to intercept.

### b. Launch Phase

The actions of the ship are controlled in the
launch phase once an engagement decision has been reached.
A launch record for the weapon to target pairing is created
and entered into the queue of launches. The delays of the
actual SAM launcher are modeled to simulate reality. Once
the SAM is fired, the missile inventory in the ship's
magazine is decremented.

### c. Intercept Phase

The actual intercept event of SAM flyout and
outcome determination(kill assessment) are represented in
the Intercept Phase. The kill assessment allows for a delay
in the evaluation of the success of the engagement before
the track is either removed from the engagement file in the

case of a kill, or rescheduled for another intercept attempt in the event of a failure.

Several checks are executed in the intercept portion of this phase to determine the outcome of the engagement. Provided the firing ship and TBM are still alive in the simulation and the TBM track is held by the firing unit, the TBM's survival will be assessed against the SAM's capability. If the range to the TBM is greater than the lethal range of the weapon against it, or if the ship's radar no longer holds the TBM, the engagement is a failure. The target is then evaluated against the $P_k$ of the weapon fired at it through a random draw. If the $P_k$ is greater than the random draw, the engagement is a success.

### d. Reload Phase

In this scenario, the reload phase is not utilized. The ship's magazines are filled with 80 SAMs. Of these, 40 are Upper Tier weapons, capable only against TBMs in high altitude, and 40 Lower Tier weapons which are available for any anti-aircraft engagements. Once these missiles are depleted, replenishment from a pier, tender, or other method must be sought. Replenishment of these weapons would take the ship out of action for days; scheduling a replacement is not considered in this thesis. This reload feature of EADSIM would more appropriately be used in modeling a ground-based SAM site such as a PATRIOT or HAWK

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battery, which has additional missiles available in vehicles near the launch sites.

### 3. Weapon Selection

The weapon selection process determines which weapon will be used to intercept the threat. This process would be used in the case of a SAM commander who has more than one type of missile available to counter a threat. An example could be a heterogeneous SAM battery ashore or an AEGIS ship in tactical command of other SAM ships in defense of an area or high-value unit. Weapons are selected for engaging threats based on the shortest intercept time to the target.

### 4. Firing Doctrine

The number of SAMs shot against a target is dependent upon the difficulty and urgency of the engagement. For an urgent, challenging shot against a high velocity target such as a TBM, the primary doctrine is to launch two missiles at each target as rapidly as the launcher is capable, and then observe the result. Should the intercept fail, another two missiles will be fired(SHOOT-SHOOT, LOOK, SHOOT-SHOOT). Once the missile magazine is decremented to a certain level or threshold, normally 50 percent of its full capacity of that weapon, a secondary doctrine of one SAM per TBM(SHOOT, LOOK, SHOOT) is established to conserve missiles for possible future firings.

### 5. TBM Flight

The TBM is modeled as a surface-to-surface missile with a single-stage rocket motor. It can fly two profiles, either lofted or depressed, which are user-selected. These profiles are accomplished through a launch iteration scheme given the range to the intended target. The flight of the TBM is modeled through numerical integration of three-degrees-of-freedom(3 dof) equations of motion. The effects of gravity and altitude-dependent atmospheric pressure are accommodated also. It is assumed that the TBM flies along its velocity(thrust) vector properly trimmed during its flight.

It is conceived that the enemy, knowing the exact range to his target from his firing position, would load his missile with only the minimum fuel necessary to deliver it to the target. This is termed a *minimum energy trajectory*. Its purpose is to reduce the missile's probability of being intercepted by minimizing its flight time while keeping the trajectory higher than the depressed flight. Theoretically this would lessen the TBMs exposure time in the lethal area of the TBM defenses.

The simulation version used currently does not support minimum energy trajectories. This is corrected in the models's next release, version 3.0. In view of current and near-term technology, it is reasonable to assume that a

long-range TBM would fly in a *lofted* trajectory.  This was the trajectory modeled for the scenario.

## B. HARDWARE DESCRIPTION

EADSIM requires a powerful, but not necessarily unique, computer system to take advantage of the graphics and data processing attributes of the model:

-Silicon Graphics 4D-series workstation with 24-bit plane graphics

-UNIX operating system

-64MB RAM

-1.2GB disk storage

In its next release, version 3.0, the model can be run on a smaller, less-expensive, Sun Sparc2 or Sparc10 workstation, provided it has a GS graphics card.  Only a moderate degradation in graphics capability of the simulation is reported.  These workstations are the Navy's standard desktop workstations and are being acquired in large numbers for both sea and shore activities.

## C. DESIGN OF THE EXPERIMENT

A series of trials are run to adequately and reliably measure the response of interest, in this case, TBM kills, as position of the AEGIS ship is varied.  Although this scenario could be modeled more realistically as a complex theater level wargame with thousands of platforms and

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variables, in this thesis, the AEGIS ship position will be the factor that influences the experiment's results.

The intent of this model is to determine the best position for the ship to produce the maximum value of the response, e.g., maximizing AEGIS TBM kills. This design choice was also chosen for its military applicability.

Without superb intelligence estimates of the enemy's intentions, a commander must position his forces so as to counter any perceived enemy action. As more information on enemy intentions is obtained and evaluated, defending resources are adjusted to increase their advantage against the enemy.

At the outset of this scenario, the only intelligence available is that since Libya has 12 launch vehicles, Libya has the potential to fire a maximum of 12 TBMs in a raid. Thus the worst-case number of TBMs in flight is defined. No other information is known by the West other than that relations with Libya are strained and tense. As a non-provocative precaution, an AEGIS ship is tasked to defend Central Italian cities while conducting operations in international waters in the Mediterranean Sea.

# IV. ANALYSIS

## A. PRELIMINARY STATIONING RESULTS

Using the scenario described in Chapter II(Scenario Description, Enemy Capabilities) and the methodology addressed in Chapter III, one replication of the simulation for each of 61 different geographic stationing positions(by latitude and longitude) to defend both cities was done. The results of the runs are found in Appendix A. The number of TBM hits on the cities was recorded in order to compare the firing ship's position against the measure of effectiveness.

Knowing that a 12-TBM raid of six TBMs at each city was launched, a percent attrition of the raid by the AEGIS ship for each city is calculated and appears in Appendix A, also. Included among these defensive stations were those that were expected not to intercept many TBMs. This was necessary in order to show the rises in the contour and three dimensional surface plots: the Response Surfaces. These plots enhance visualization of the most effective AEGIS stationing assignment areas and indicate those where the estimated effectiveness of the ship is quite low(Figure 2).

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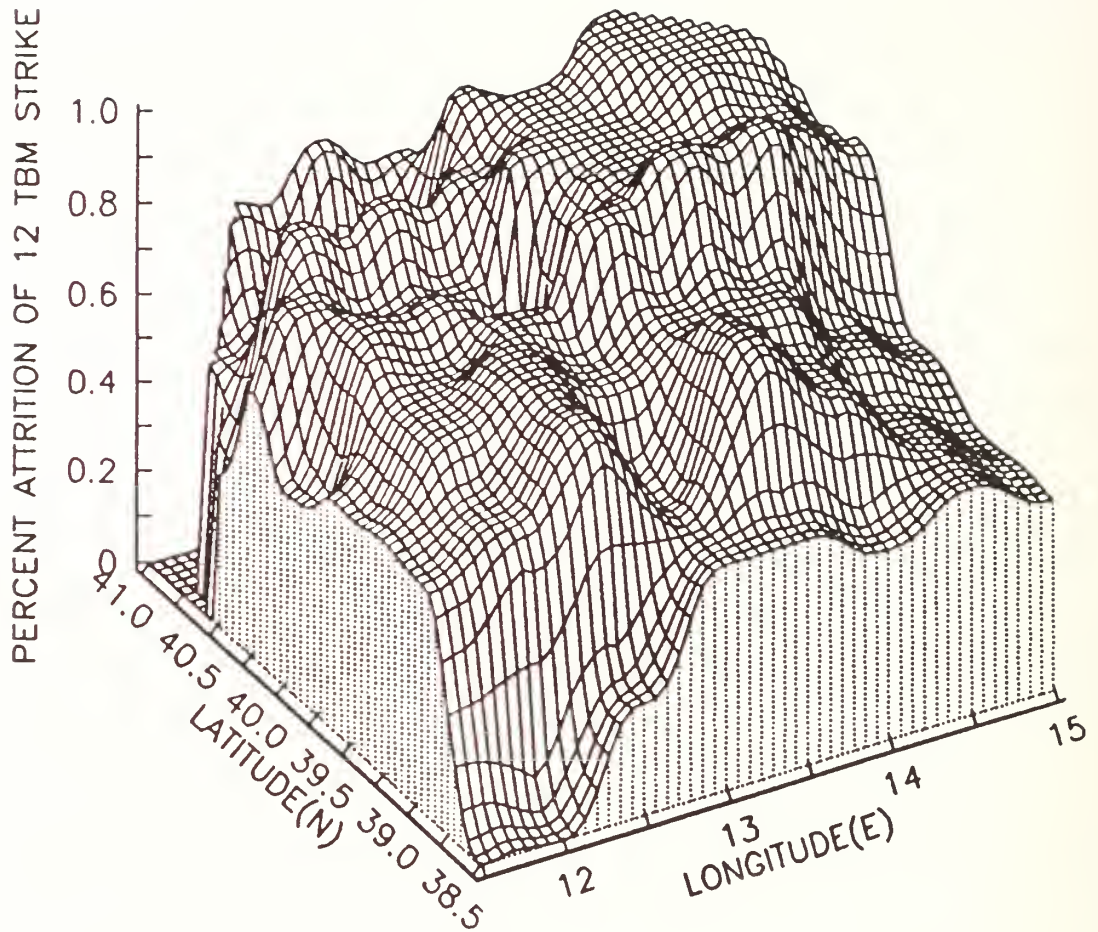
**FIGURE 2.** Surface Plot of Average TBM Attrition

## B. MONTE CARLO EVALUATION OF STATIONING RESULTS

From this first set of trials run to obtain a
familiarity with the AEGIS ship performance, 33 of the
original positions tested as moderately satisfactory at
meeting the measure of effectiveness of two or less TBMs
surviving to impact each city. Thus, further testing was

required on these positions to gain a more precise estimate
of expected TBM hits on the cities and their variance.

This was accomplished by evaluating the AEGIS ship in
each of those satisfactory positions through ten Monte Carlo
replications using a different random number seed for the
C3I and Detection process for each trial. Random number
seeds were drawn from a function in a HP-28C calculator.
The results of these trials are found in Appendix B.

The number of hits on each city were averaged over the
ten Monte Carlo trials of each position. This average is
the mean number of hits on the city and describes the
estimated expected number of hits on the city per TBM strike
mission(termed EXP VAL in Appendix B). Data from these
trials was also used to calculate the sample variance of the
number of hits and standard error of the mean number of TBM
hits upon each city. The square of the standard error is
the sample variance divided by the number of replications,
which is 10. Formulas for these calculations appear in
Appendix B.

There were no TBM failures in flight modeled in this
study. Therefore, TBMs that did not impact the city were
evaluated as being killed by the AEGIS ship. Thus, an AEGIS
ship's probability of killing an individual TBM targeted at
a specified city is computed from the data collected from
each ship position and appears in Appendix B. An average of
the estimated AEGIS ship probabilities of a TBM kill for the

two cities was determined. This was used as an estimate of the AEGIS ship probability of killing an incoming TBM targeted against either city, or average attrition, which is shown in Figure 2.

The probability of an individual TBM impact on a city was determined using the converse of the probability of it being intercepted by an AEGIS SAM, or $(1-\text{Pr}_{\text{TBM kill}})$ indexed on the city. These probabilities are tabulated in Appendix C. From these, the estimated probabilities of zero, one, and two TBM hits on a city were computed. These probabilities were calculated using a sum of the two distinct binomial probability distributions of individual TBM hits on the target cities, given the position of the defending ship.

The needed calculations are given below; ^ indicates an estimate from simulation output.

$$\hat{Pr}(0\ hits) = (1-\hat{P}_{h_{Rome}})^6 + (1-\hat{P}_{h_{Naples}})^6 \tag{1}$$

$$\hat{Pr}(1\ hit) = (1-\hat{P}_{h_{Rome}})^6 (6\hat{P}_{h_{Naples}})(1-\hat{P}_{h_{Naples}})^5$$
$$+ (1-\hat{P}_{h_{Naples}})^6\ 6\hat{P}_{h_{Rome}}(1-\hat{P}_{h_{Rome}})^5 \tag{2}$$

$$\hat{Pr}(2 \; hits) = (1-\hat{P}_{h_{Rome}})^6 \; 3\hat{P}_{h_{Naples}^2} \; (1-\hat{P}_{h_{Naples}})^4$$
$$+ \; 6P_{h_{Rome}}(1-\hat{P}_{h_{Rome}})^5 \; 6\hat{P}_{h_{Naples}}(1-\hat{P}_{h_{Naples}})^5 \qquad (3)$$
$$+ \; (1-\hat{P}_{h_{Naples}})^6 \; 3\hat{P}_{h_{Rome}}{}^2 \; (1-\hat{P}_{h_{Rome}})^4$$

$$\hat{Pr}(2 \; hits \lor fewer) = \hat{Pr}(0 \; hits) + \hat{Pr}(1 \; hit) + \hat{Pr}(2 \; hits) \qquad (4)$$

These probability calculations of the number of TBM hits to either city are tabulated in Appendix C. The positions of these ship stationing assignments and the expected number of TBM hits were plotted in a 3-dimensional scatter plot for each city as shown in Figures 3 and 4.
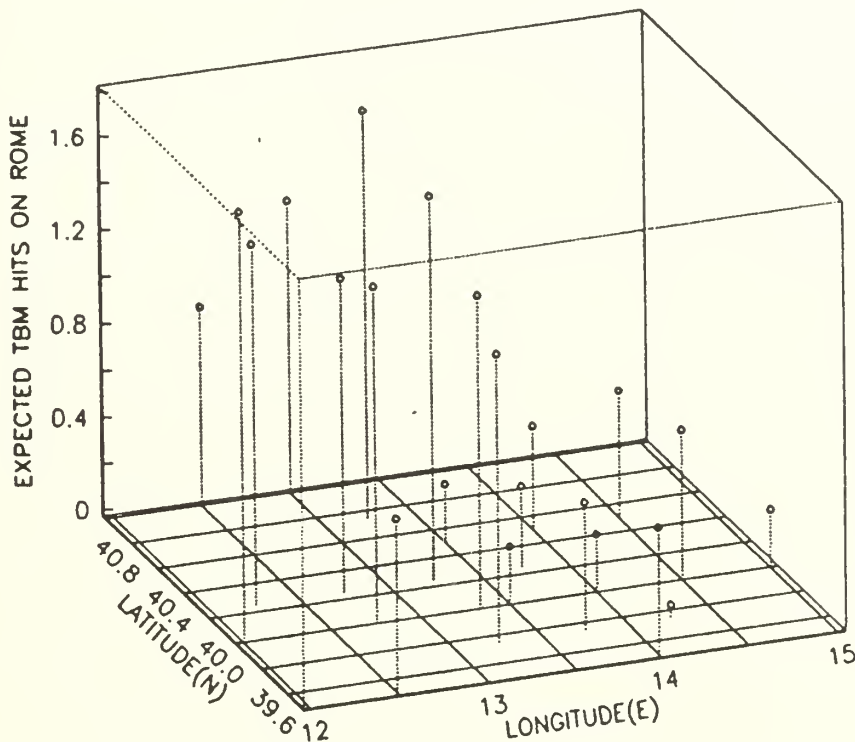


**FIGURE 3.** Scatter Plot of Expected TBM Hits on Rome
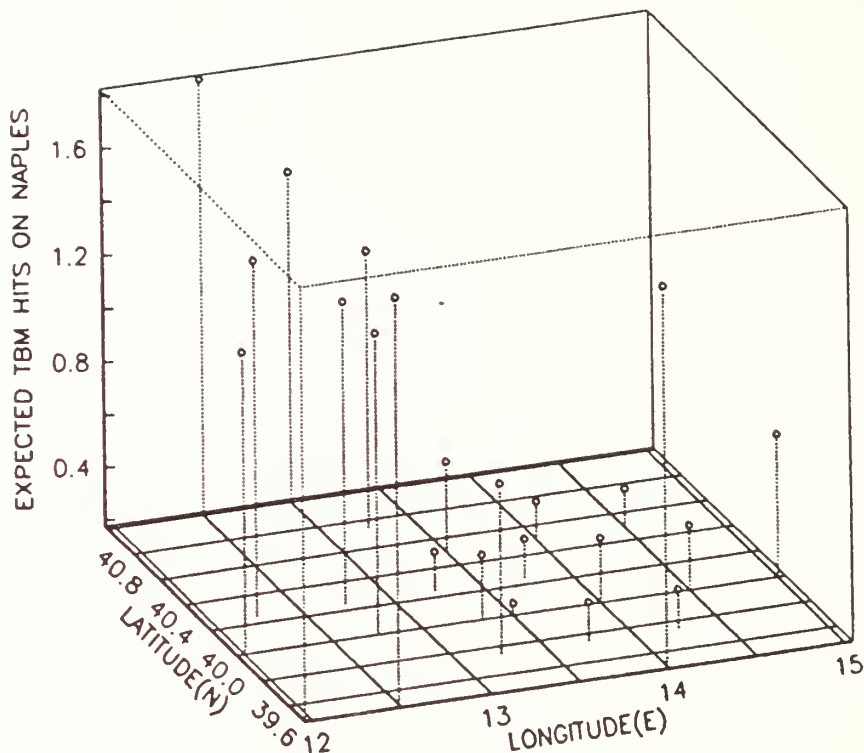
**FIGURE 4.** Scatter Plot of Expected TBM Hits on Naples

Of the 33 positions that were worthy of further
evaluation, *11 positions had two or fewer TBM hits upon both
of the cities with an estimated probability in excess of 90-
percent.* A listing of the positions are found in Appendix
C. Maximizing the estimated probability of two or fewer
hits is the objective selected to satisfy the measure of
effectiveness. A display of those results in graphed in
Figure 5.
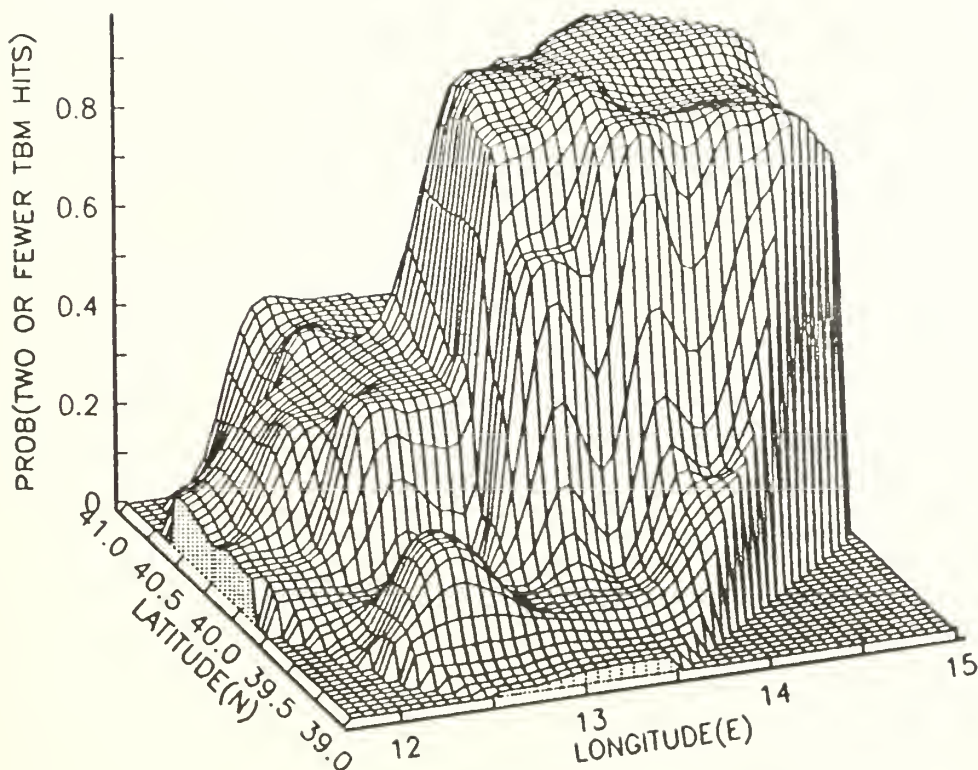
**FIGURE 5.** Surface Plot of the Estimated Probability of Two
or fewer TBM hits per city

Stationing the ship at 39.75 degrees (North) and 14.25
degrees (East) results in a estimated 98-percent probability
of destroying individual TBMs, as calculated in the last
column of Appendix B(AVE[Pr(INDIV TBM KILL)]). In ten
trials with the ship stationed at the above coordinates,
there were no hits on Rome and only an expected 0.30 hits
per raid upon Naples. Combined with an estimated 94-percent
probability of both cities sustaining two or fewer TBM hits;
this position clearly exceeds the measure of effectiveness

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described previously. This compares favorably with a contour plot of the estimated AEGIS ship probabilities of a TBM kill against individual TBMs as depicted in Figure 6 below.
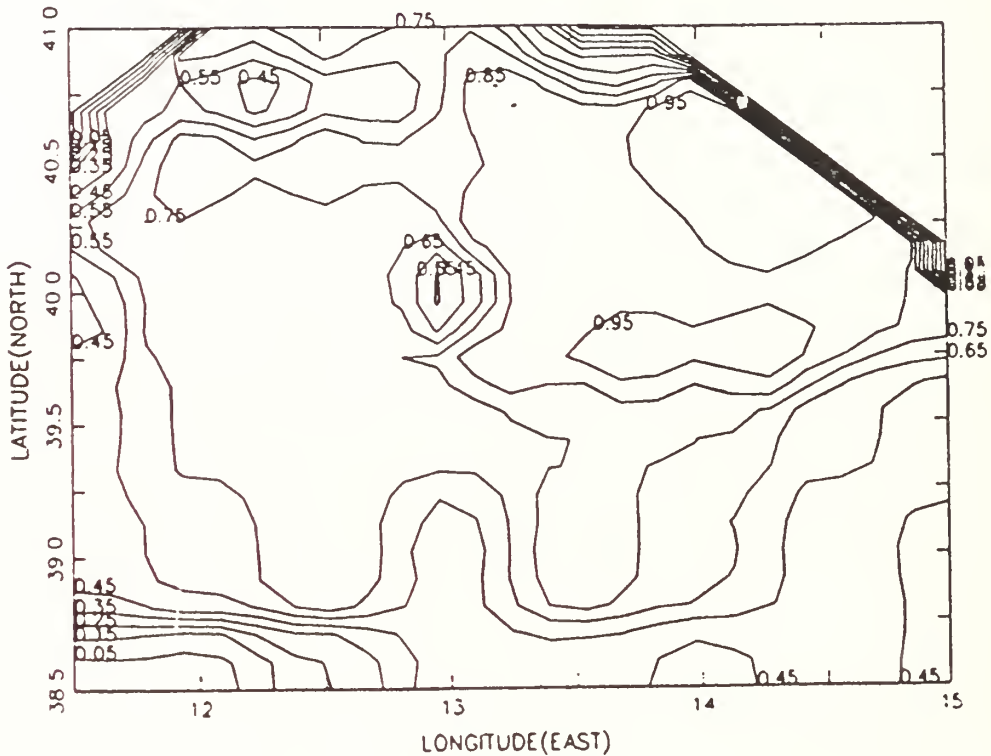


**FIGURE 6.** Contour Plot of AEGIS Attrition of TBMs

It accurately shows the bounds of the most effective operating areas to position the ship. The upper right quadrant of the plot represents the Italian coastline, and thus is unavailable for ship stationing.

## C. MODEL WEAKNESSES

The experience gained over several months to simulate this scenario has illuminated some weaknesses in the simulation. First, the model was created for the U.S. Army; hence there has been little Navy involvement in its development. Tailoring of Army and Air Force systems were required to approximate naval systems and operations. As the Navy embraces EADSIM, it is recommended that a notional AEGIS model be developed and validated by the AEGIS Program Office(PMS400) for an accurate representation of the ship's systems.

EADSIM requires an in-depth knowledge of C2 architectures, Anti-air Warfare(AAW) systems, and the TBM threat. It is difficult for one person to have a thorough background in all of these warfare disciplines. Therefore, for the most accurate representation of a scenario, a heterogeneous team with combined experience in various aspects of Theater Missile Defense would be most beneficial.

Despite the use of a graphical user interface(GUI) for data input and model operation, EADSIM is not user-friendly from an average staff officer's perspective. Interviews with other users throughout the country confirm this opinion. An estimate of two to four man-months to create a theater-level scenario with 2,000 platforms is ambitiously optimistic unless the staff is well-practiced. A week-long tailored training session for the author of this thesis was

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necessary in order to utilize the basic features and generate this simple scenario. There are EADSIM user's groups throughout the country that meet frequently. These concerned users share their knowledge and recommend improvements to the model to the developer and Program Manager.

For weapons engineers, the rather simplistic modeling of $P_k$ lacks fidelity. The end-game constraints or terminal events of the SAM and TBM intercept should be more accurately modeled to properly evaluate the interceptor's effectiveness. More important than range, the aspect angles, velocity, and geometry of the two missiles at intercept are strong factors in SAM effectiveness. But the dynamics of those constraints could be accounted for through a lower user-defined $P_k$ of the SAMs. This $P_k$ would be based upon a higher-fidelity detailed analysis using existing engineering models designed precisely for this purpose.

## V. RECOMMENDATIONS

The results of the trials demonstrates that one AEGIS ship could defend both Rome and Naples from TBMs fired from Libya, as the attacking and defending systems were modeled for the scenario.  It was expected that more than one AEGIS ship would be required to provide this defense.  From the results obtained, it is recommended that the ship be stationed in a 60 by 25 nautical mile area around 39.75 degrees(N) 14.25 degrees (E).  This provides a 1500 square nautical mile area in which the ship may operate effectively in the TMD role.

### A. NEAR-LAND STATIONING CONCERNS

Placing a ship as close as possible to the area to be defended could be a promising tactic provided that the commander is certain that the city in that area is the only one targeted by his enemy's TBMs.  In this inshore position, the AEGIS system performs best, but the inherent mobility of a warship is lost.

The placement of a ship close to a single area is far from optimum, however, because at least one ship would be required for each area defended and the debris from successful engagements could fall on friendly, heavily-populated ground.  Unfortunately, despite a successful

intercept, Weapons of Mass Destruction(WMD), could still be effective against the target cities and population if intercepted too close to the target.

If there were adequate time available prior to hostilities, upgraded PATRIOT batteries could be deployed to the cities to defend against TBMs in the terminal phase. This would free the ship from a constricted, limiting picket station to a position farther out to sea. Netted with the PATRIOT batteries, such positioning would allow more intercepts of the TBMs through defense-in-depth.

## B. DISTANT STATIONING CONCERNS

Stationing a ship farther from the city defends a much greater area, has the potential for more kills, and allows for debris and the harmful effects of WMDs to fall into the sea, away from friendly territory. Distant from land, a ship may be able to support other phases of the naval campaign and would be free to maneuver to avoid and combat other attacks, especially by enemy submarines that prey on ships whose maneuvers are too predictable.

## C. FURTHER AREAS OF STUDY

### 1. Weapon Requirements

Should the scenario described in this study be typical of future conflicts, a requirements assessment of interceptors to counter long-range TBMs must be studied.

The necessary drawdown of forces and subsequent reduction of ships will permit fewer AEGIS ships to be available for TBM defense missions. This predicament compels the design of more capable weapon systems to defeat TBMs, since fewer platforms will be in the inventory.

## 2. Firing Doctrines for Anti-TBM Defense

With the AEGIS ship's mission to intercept only 12 TBMs in the scenario modeled, only the primary SAM firing doctrine(described in Chapter III, Simulation Description, Firing Doctrine) was utilized, since the ship's missile magazine was never decremented below 50-percent. A larger TBM raid might force a change in the firing doctrine used and produce fewer TBM kills.

After actual test firings of the Anti-TBM missiles are conducted, real data will be obtained on missile performance. These data can be used with EADSIM to investigate firing schemes so as to reach an effective tactical employment doctrine. This simulation analysis would reduce the great expense of numerous exercise firings, which are destructive tests, and hence costly. Not only is the cost of missile testing a concern from a monetary perspective, but an effective combat firing doctrine is important, too.

It is imperative not to overuse missile assets in combat. An AEGIS cruiser has a maximum of 122 missile cells(AEGIS destroyers have 96), which contain a mixture of

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Land-Attack Cruise Missiles, Anti-ship Cruise Missiles, Anti-Submarine Rockets, and Anti-Air Missiles; none of which can be replenished at sea.  An inport period or mooring to a tending vessel in very calm waters must be scheduled to effect a replenishment of missiles.  So what may be a successful firing doctrine on the first day of the "TBM Campaign" may not be so by the third day, when the SAMs have been expended and the ship must leave station to be replenished.  Should the TBM threat remain present, another AEGIS ship would be required to perform this role when the first departs its station for replenishment.

### 3. Multi-ship Stationing Plans

Defending a larger area, perhaps even an entire theater against missile attack, could be modeled in EADSIM. This would take the form of a theater-level model with hundreds of platforms, including land-based air defenses and enemy tactical aircraft.  The simulation can model multiple platforms in the theater air defense network.  Studies in this area could aid in determining a proper Theater Missile Defense force structure required to astutely build for future regional conflicts.

### 4. Joint Action

Outcomes of TBM scenarios will vary greatly depending upon the geography of the land to be defended. Obviously this would impact the sea room in which to station a ship and the ballistic flight profile of a TBM towards its

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target.  Cases in which Army PATRIOT and future Ground-
Based Interceptors(GBI) can be utilized should be modeled in
concert with AEGIS ships.  In the scenario presented,
PATRIOT batteries in the targeted cities could have
intercepted the remaining TBMs that penetrated the AEGIS air
defense.  Unfortunately, the cost of these advanced air
defense systems may prohibit many countries from procuring
them.  Additionally, host-country politics could prevent
nations from requesting US assistance to defend their cities
from Anti-TBM sites on their own soil.  This is one of the
great advantages of the sea-based system which operates
freely in international waters.  However, should the ground-
based batteries be available for deployment and be accepted
in the host country, it would be the most highly-sought
arrangement to properly defend the cities through a system
of layered defenses.

    With continued refinement of the simulation, more Monte
Carlo trials to reduce sampling variances, and more accurate
classified data from the sponsoring agencies on US and enemy
TBM capability, it is hoped that a more realistic response
surface for the measures of effectiveness of evaluating the
position of an AEGIS ship can be constructed.  It could then
be used as a tactical decision aid to enable a warfare
commander to best allocate assets to defend against the
growing and difficult threat represented by surface-to-

surface ballistic missiles launched from unanticipated,

unexpected, and difficult to neutralize sources.

.

RESULTS OF SIMULATION RUNS

$$Raid\ Attrition = Nr\ TBM\ hits_{city}/Nr\ TBMs\ fired_{city}\ \epsilon raid$$

$$Average = (Raid\ Attrition_{Rome} + Raid\ Attrition_{Naples})/2$$

| POS | SHIP LOCATION | | SIMULATION RESULTS | | | Raid Attrition | | |
|-----|------|------|------|--------|---|------|--------|---------|
| | Lat(N) | Long(E) | (TBM IMPACTS) | | | | | |
| | | | Rome | Naples | | Rome | Naples | Average |
| 1 | 40.50 | 12.50 | 2 | 0 | | 0.67 | 1.00 | 0.83 |
| 2 | 40.50 | 12.00 | 1 | 1 | | 0.83 | 0.83 | 0.83 |
| 3 | 40.50 | 13.00 | 2 | 0 | | 0.67 | 1.00 | 0.83 |
| 4 | 40.50 | 13.50 | 0 | 1 | | 1.00 | 0.83 | 0.92 |
| 5 | 40.75 | 13.25 | 0 | 1 | | 1.00 | 0.83 | 0.92 |
| 6 | 40.75 | 12.75 | 5 | 0 | | 0.17 | 1.00 | 0.58 |
| 7 | 40.75 | 12.25 | 4 | 3 | | 0.33 | 0.50 | 0.42 |
| 8 | 40.75 | 11.75 | 0 | 6 | | 1.00 | 0.00 | 0.50 |
| 9 | 40.25 | 13.75 | 1 | 0 | | 0.83 | 1.00 | 0.92 |
| 10 | 40.25 | 13.25 | 1 | 0 | | 0.83 | 1.00 | 0.92 |
| 11 | 40.25 | 12.75 | 2 | 2 | | 0.67 | 0.67 | 0.67 |
| 12 | 40.25 | 12.25 | 3 | 1 | | 0.50 | 0.83 | 0.67 |
| 13 | 41.00 | 12.50 | 0 | 2 | | 1.00 | 0.67 | 0.83 |
| 14 | 41.00 | 12.00 | 0 | 3 | | 1.00 | 0.50 | 0.75 |
| 15 | 41.00 | 13.00 | 1 | 2 | | 0.83 | 0.67 | 0.75 |
| 16 | 41.00 | 13.50 | 5 | 3 | | 0.17 | 0.50 | 0.33 |
| 17 | 40.00 | 13.50 | 1 | 0 | | 0.83 | 1.00 | 0.92 |
| 18 | 40.00 | 13.00 | 2 | 5 | | 0.67 | 0.17 | 0.42 |
| 19 | 40.00 | 13.25 | 2 | 0 | | 0.67 | 1.00 | 0.83 |
| 20 | 40.00 | 13.33 | 1 | 0 | | 0.83 | 1.00 | 0.92 |
| 21 | 40.00 | 12.50 | 1 | 2 | | 0.83 | 0.67 | 0.75 |
| 22 | 40.00 | 12.75 | 2 | 2 | | 0.67 | 0.67 | 0.67 |
| 23 | 39.50 | 13.00 | 2 | 2 | | 0.67 | 0.67 | 0.67 |
| 24 | 39.50 | 13.50 | 1 | 2 | | 0.83 | 0.67 | 0.75 |
| 25 | 39.50 | 12.50 | 1 | 2 | | 0.83 | 0.67 | 0.75 |
| 26 | 39.50 | 14.00 | 0 | 3 | | 1.00 | 0.50 | 0.75 |
| 27 | 39.50 | 14.50 | 1 | 4 | | 0.83 | 0.33 | 0.58 |
| 28 | 39.50 | 15.00 | 6 | 0 | | 0.00 | 1.00 | 0.50 |
| 29 | 39.50 | 12.00 | 1 | 3 | | 0.83 | 0.50 | 0.67 |
| 30 | 40.00 | 12.00 | 1 | 2 | | 0.83 | 0.67 | 0.75 |

# APPENDIX A

## RESULTS OF SIMULATION RUNS

| RUN | LOCATION | | RESULTS | | | | | |
|-----|--------|---------|---------|--------|---|------|------|------|
| | Lat(N) | Long(E) | (Nr of TBM's that proceed to cities) | | | | | |
| | | | Rome | Naples | | | | |
| 31 | 40.00 | 14.00 | 0 | 1 | | 1.00 | 0.83 | 0.92 |
| 32 | 39.00 | 12.00 | 1 | 4 | | 0.83 | 0.33 | 0.58 |
| 33 | 39.00 | 12.50 | 0 | 3 | | 1.00 | 0.50 | 0.75 |
| 34 | 39.00 | 13.00 | 1 | 5 | | 0.83 | 0.17 | 0.50 |
| 35 | 39.00 | 13.50 | 0 | 2 | | 1.00 | 0.67 | 0.83 |
| 36 | 39.00 | 14.00 | 4 | 0 | | 0.33 | 1.00 | 0.67 |
| 37 | 39.00 | 14.50 | 6 | 0 | | 0.00 | 1.00 | 0.50 |
| 38 | 39.00 | 15.00 | 6 | 1 | | 0.00 | 0.83 | 0.42 |
| 39 | 40.00 | 14.50 | 1 | 0 | | 0.83 | 1.00 | 0.92 |
| 40 | 40.00 | 15.00 | 1 | 1 | | 0.83 | 0.83 | 0.83 |
| 41 | 39.00 | 11.50 | 0 | 6 | | 1.00 | 0.00 | 0.50 |
| 42 | 38.50 | 11.50 | 6 | 6 | | 0.00 | 0.00 | 0.00 |
| 43 | 38.50 | 12.00 | 6 | 6 | | 0.00 | 0.00 | 0.00 |
| 44 | 38.50 | 12.50 | 6 | 3 | | 0.00 | 0.50 | 0.25 |
| 45 | 38.50 | 13.00 | 6 | 0 | | 0.00 | 1.00 | 0.50 |
| 46 | 38.50 | 13.50 | 6 | 0 | | 0.00 | 1.00 | 0.50 |
| 47 | 38.50 | 14.00 | 6 | 1 | | 0.00 | 0.83 | 0.42 |
| 48 | 38.50 | 14.50 | 6 | 0 | | 0.00 | 1.00 | 0.50 |
| 49 | 38.50 | 15.00 | 6 | 1 | | 0.00 | 0.83 | 0.42 |
| 50 | 40.25 | 14.25 | 0 | 0 | | 1.00 | 1.00 | 1.00 |
| 51 | 40.25 | 11.75 | 1 | 2 | | 0.83 | 0.67 | 0.75 |
| 52 | 40.00 | 11.50 | 1 | 6 | | 0.83 | 0.00 | 0.42 |
| 53 | 39.50 | 11.50 | 6 | 0 | | 0.00 | 1.00 | 0.50 |
| 54 | 39.75 | 14.25 | 0 | 0 | | 1.00 | 1.00 | 1.00 |
| 55 | 39.75 | 13.75 | 0 | 0 | | 1.00 | 1.00 | 1.00 |
| 56 | 39.75 | 13.25 | 1 | 0 | | 0.83 | 1.00 | 0.92 |
| 57 | 39.75 | 12.75 | 0 | 3 | | 1.00 | 0.50 | 0.75 |
| 58 | 39.75 | 12.25 | 1 | 3 | | 0.83 | 0.50 | 0.67 |
| 59 | 40.50 | 14.00 | 0 | 0 | | 1.00 | 1.00 | 1.00 |
| 60 | 40.50 | 14.50 | 0 | 0 | | 1.00 | 1.00 | 1.00 |
| 61 | 40.50 | 11.50 | 2 | 6 | | 0.67 | 0.00 | 0.33 |

# APPENDIX B

## RESULTS OF MONTE CARLO TRIALS OF PREFERRED SHIP POSITIONS

$$EXP\ VAL_{city} = (\sum_{n=1}^{10} TBM\ hits_{city}(n))\ /\ 10$$

$$SAMPLE\ VAR = (\sum_{n=1}^{10} (Nr\ TBM\ hits_{city}(n) - EXP\ VAL_{city})^2)\ /\ 9$$

$$Standard\ \epsilon\ of\ EST\ EXP\ VAL_{city} = \sqrt{VAR_{city}}\ /\ \sqrt{10}$$

$$\hat{Pr}(INDIV\ TBM\ KILL_{city}) =$$
$$(\sum_{n=1}^{10} (Nr\ of\ TBMs\ fired_{city} - Nr\ of\ TBM\ hits_{city})(n))\ /\ 60$$

$$AVE[\hat{Pr}(INDIV\ TBM\ KILL)] =$$
$$(\hat{Pr}(INDIV\ TBM\ KILL_{Rome}) + \hat{Pr}(INDIV\ TBM\ KILL_{Naples}))\ /\ 2$$

n = replication nı

RESULTS OF MONTE CARLO TRIALS OF PREFERRED SHIP POSITIONS

| POS | | TBM HITS ON CITIES (BY TRIAL NUMBER) | | | | | | | | | | EXP VAL | VAR | STD ERROR OF EST EXP VAL | Pr (INDIV TBM KILL) | WEPPON/TBM KILL// |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | | | | | |
| 4 | 40.5N/13.5E | | | | | | | | | | | | | | | 0.94 |
| | Rome Hits | 0 | 0 | 1 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0.20 | 0.18 | 0.13 | 0.97 | |
| | Naples Hits | 1 | 0 | 1 | 1 | 0 | 1 | 0 | 1 | 0 | 1 | 0.50 | 0.28 | 0.17 | 0.92 | |
| 5 | 40.75N/13.25E | | | | | | | | | | | | | | | 0.76 |
| | Rome Hits | 0 | 2 | 1 | 1 | 1 | 2 | 4 | 2 | 2 | 2 | 1.70 | 1.12 | 0.33 | 0.72 | |
| | Naples Hits | 1 | 1 | 1 | 2 | 1 | 1 | 1 | 1 | 1 | 2 | 1.20 | 0.18 | 0.13 | 0.80 | |
| 9 | 40.25N/13.75E | | | | | | | | | | | | | | | 0.95 |
| | Rome Hits | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 0.80 | 0.23 | 0.15 | 0.95 | |
| | Naples Hits | 0 | 1 | 0 | 0 | 1 | 0 | 0 | 0 | 1 | 1 | 0.80 | 0.23 | 0.15 | 0.95 | |
| 10 | 40.25N/13.25E | | | | | | | | | | | | | | | 0.84 |
| | Rome Hits | 1 | 2 | 1 | 1 | 1 | 3 | 2 | 2 | 2 | 1 | 1.60 | 0.49 | 0.22 | 0.73 | |
| | Naples Hits | 0 | 0 | 0 | 0 | 1 | 1 | 0 | 2 | 0 | 0 | 0.80 | 0.46 | 0.21 | 0.95 | |
| 11 | 40.25N/12.75E | | | | | | | | | | | | | | | 0.78 |
| | Rome Hits | 2 | 1 | 1 | 1 | 2 | 1 | 1 | 1 | 2 | 1 | 1.30 | 0.23 | 0.15 | 0.78 | |
| | Naples Hits | 2 | 1 | 1 | 1 | 1 | 2 | 1 | 1 | 1 | 2 | 1.30 | 0.23 | 0.15 | 0.78 | |
| 12 | 40.25N/12.25E | | | | | | | | | | | | | | | 0.75 |
| | Rome Hits | 3 | 1 | 1 | 1 | 3 | 1 | 1 | 1 | 1 | 1 | 1.50 | 0.72 | 0.27 | 0.75 | |
| | Naples Hits | 1 | 1 | 2 | 2 | 2 | 1 | 2 | 2 | 1 | 1 | 1.50 | 0.28 | 0.17 | 0.75 | |
| 13 | 41N/12.5E | | | | | | | | | | | | | | | 0.78 |
| | Rome Hits | 0 | 1 | 1 | 1 | 1 | 1 | 0 | 0 | 1 | 2 | 0.80 | 0.4 | 0.20 | 0.87 | |
| | Naples Hits | 2 | 1 | 2 | 1 | 2 | 2 | 2 | 2 | 2 | 2 | 1.60 | 0.18 | 0.13 | 0.70 | |
| 14 | 41N/12E | | | | | | | | | | | | | | | 0.71 |
| | Rome Hits | 0 | 0 | 1 | 0 | 1 | 0 | 0 | 0 | 0 | 1 | 0.30 | 0.23 | 0.15 | 0.95 | |
| | Naples Hits | 3 | 3 | 4 | 3 | 3 | 4 | 3 | 3 | 3 | 3 | 3.20 | 0.18 | 0.13 | 0.47 | |
| 15 | 41N/13E | | | | | | | | | | | | | | | 0.78 |
| | Rome Hits | 1 | 1 | 1 | 1 | 1 | 2 | 1 | 1 | 1 | 2 | 1.20 | 0.18 | 0.13 | 0.80 | |
| | Naples Hits | 2 | 1 | 1 | 1 | 2 | 2 | 1 | 1 | 1 | 1 | 1.40 | 0.27 | 0.16 | 0.77 | |
| 17 | 40N/13.5E | | | | | | | | | | | | | | | 0.97 |
| | Rome Hits | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0.20 | 0.18 | 0.13 | 0.97 | |
| | Naples Hits | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0.20 | 0.18 | 0.13 | 0.97 | |

# RESULTS OF MONTE CARLO TRIALS OF PREFERRED SHIP POSITIONS

| POS | | TBM HITS ON CITIES (BY TRIAL NUMBER) | | | | | | | | | | EXP VAL | VAR | STD ERROR OF EST EXP VAL | Pr(INDIV TBM KILL) | AVERAGE Pr(INDIV TBM KILL) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | | | | | |
| 19 | 40N/13.25E | | | | | | | | | | | | | | | |
| | Rome Hits | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 3 | 2 | 2.10 | 0.1 | 0.10 | 0.65 | 0.79 |
| | Naples Hits | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 0 | 1 | 0.40 | 0.27 | 0.16 | 0.93 | |
| 20 | 40N/13.33E | | | | | | | | | | | | | | | |
| | Rome Hits | 1 | 1 | 1 | 1 | 1 | 1 | 2 | 2 | 2 | 1 | 1.30 | 0.23 | 0.15 | 0.78 | 0.86 |
| | Naples Hits | 0 | 0 | 0 | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 0.40 | 0.27 | 0.16 | 0.93 | |
| 21 | 40N/12.5E | | | | | | | | | | | | | | | |
| | Rome Hits | 1 | 2 | 1 | 1 | 1 | 2 | 4 | 2 | 2 | 2 | 1.80 | 0.84 | 0.29 | 0.70 | 0.74 |
| | Naples Hits | 2 | 1 | 1 | 2 | 1 | 1 | 1 | 1 | 2 | 1 | 1.30 | 0.23 | 0.15 | 0.78 | |
| 22 | 40N/12.75E | | | | | | | | | | | | | | | |
| | Rome Hits | 2 | 2 | 1 | 1 | 1 | 2 | 2 | 1 | 1 | 1 | 1.40 | 0.27 | 0.16 | 0.77 | 0.78 |
| | Naples Hits | 2 | 1 | 2 | 1 | 1 | 1 | 1 | 1 | 1 | 2 | 1.30 | 0.23 | 0.15 | 0.78 | |
| 23 | 39.5N/13E | | | | | | | | | | | | | | | |
| | Rome Hits | 2 | 0 | 0 | 0 | 1 | 0 | 1 | 0 | 0 | 0 | 0.40 | 0.49 | 0.22 | 0.93 | 0.78 |
| | Naples Hits | 2 | 2 | 3 | 2 | 2 | 2 | 2 | 3 | 3 | 2 | 2.30 | 0.23 | 0.15 | 0.62 | |
| 24 | 39.5N/13.5E | | | | | | | | | | | | | | | |
| | Rome Hits | 1 | 1 | 0 | 0 | 0 | 0 | 2 | 0 | 0 | 2 | 0.60 | 0.71 | 0.27 | 0.90 | 0.76 |
| | Naples Hits | 2 | 2 | 3 | 2 | 3 | 2 | 3 | 2 | 2 | 2 | 2.30 | 0.23 | 0.15 | 0.62 | |
| 25 | 39.5N/12.5E | | | | | | | | | | | | | | | |
| | Rome Hits | 1 | 0 | 0 | 0 | 2 | 1 | 1 | 0 | 1 | 1 | 0.70 | 0.46 | 0.21 | 0.88 | 0.80 |
| | Naples Hits | 2 | 2 | 1 | 2 | 1 | 3 | 1 | 1 | 3 | 1 | 1.70 | 0.68 | 0.26 | 0.72 | |
| 26 | 39.5N/14E | | | | | | | | | | | | | | | |
| | Rome Hits | 0 | 1 | 0 | 1 | 0 | 1 | 0 | 1 | 1 | 0 | 0.50 | 0.28 | 0.17 | 0.92 | 0.83 |
| | Naples Hits | 3 | 1 | 1 | 1 | 3 | 2 | 2 | 1 | 1 | 1 | 1.60 | 0.71 | 0.27 | 0.73 | |
| 28 | 39.5N/12E | | | | | | | | | | | | | | | |
| | Rome Hits | 1 | 0 | 2 | 0 | 1 | 0 | 1 | 0 | 1 | 0 | 0.60 | 0.49 | 0.22 | 0.90 | 0.69 |
| | Naples Hits | 3 | 3 | 3 | 3 | 4 | 3 | 3 | 3 | 3 | 3 | 3.10 | 0.1 | 0.10 | 0.48 | |
| 30 | 40N/12E | | | | | | | | | | | | | | | |
| | Rome Hits | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 2 | 1 | 1.20 | 0.18 | 0.13 | 0.80 | 0.72 |
| | Naples Hits | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 3 | 3 | 2.20 | 0.18 | 0.13 | 0.63 | |

# APPENDIX B

RESULTS OF MONTE CARLO TRIALS OF PREFERRED SHIP POSITIONS

| POS | | TBM HITS ON CITIES (BY TRIAL NUMBER) 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | EXP VAL | VAR | STD ERROR OF EST EXP VAL | Pr( INDIV TBM KILL) | AVE Pr/INDIV TBM KILL/// |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 31 | 40N/14E | | | | | | | | | | | | | | | 0.95 |
| | Rome Hits | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 1 | 0 | 0.20 | 0.18 | 0.13 | 0.97 | |
| | Naples Hits | 1 | 0 | 1 | 0 | 0 | 1 | 0 | 1 | 0 | 0 | 0.40 | 0.27 | 0.16 | 0.93 | |
| 33 | 39N/12.5E | | | | | | | | | | | | | | | 0.72 |
| | Rome Hits | 0 | 1 | 0 | 0 | 0 | 1 | 1 | 0 | 0 | 0 | 0.30 | 0.23 | 0.15 | 0.95 | |
| | Naples Hits | 3 | 3 | 4 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3.10 | 0.1 | 0.10 | 0.48 | |
| 35 | 39N/13.5E | | | | | | | | | | | | | | | 0.77 |
| | Rome Hits | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0.10 | 0.1 | 0.10 | 0.98 | |
| | Naples Hits | 2 | 2 | 2 | 2 | 4 | 3 | 4 | 3 | 2 | 3 | 2.70 | 0.68 | 0.26 | 0.55 | |
| 39 | 40N/14.5E | | | | | | | | | | | | | | | 0.92 |
| | Rome Hits | 1 | 0 | 3 | 0 | 1 | 0 | 1 | 0 | 0 | 0 | 0.60 | 0.93 | 0.31 | 0.90 | |
| | Naples Hits | 0 | 0 | 0 | 2 | 0 | 0 | 0 | 0 | 2 | 0 | 0.40 | 0.71 | 0.27 | 0.93 | |
| 40 | 40N/15E | | | | | | | | | | | | | | | 0.83 |
| | Rome Hits | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.20 | 0.18 | 0.13 | 0.97 | |
| | Naples Hits | 1 | 0 | 0 | 2 | 0 | 1 | 1 | 0 | 1 | 1 | 0.70 | 0.46 | 0.21 | 0.88 | |
| 51 | 40.25N/11.75E | | | | | | | | | | | | | | | 0.72 |
| | Rome Hits | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 2 | 1 | 1.10 | 0.1 | 0.10 | 0.82 | |
| | Naples Hits | 2 | 2 | 3 | 2 | 3 | 2 | 2 | 3 | 2 | 2 | 2.30 | 0.23 | 0.15 | 0.62 | |
| 54 | 39.75N/14.25E | | | | | | | | | | | | | | | 0.98 |
| | Rome Hits | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.00 | 0 | 0.00 | 1.00 | |
| | Naples Hits | 0 | 0 | 1 | 0 | 1 | 0 | 0 | 1 | 0 | 0 | 0.30 | 0.23 | 0.15 | 0.95 | |
| 55 | 39.75N/13.75E | | | | | | | | | | | | | | | 0.93 |
| | Rome Hits | 0 | 1 | 0 | 1 | 0 | 0 | 0 | 1 | 2 | 0 | 0.50 | 0.5 | 0.22 | 0.92 | |
| | Naples Hits | 0 | 0 | 1 | 0 | 0 | 1 | 0 | 0 | 1 | 0 | 0.30 | 0.23 | 0.15 | 0.95 | |
| 56 | 39.75N/13.25E | | | | | | | | | | | | | | | 0.83 |
| | Rome Hits | 1 | 0 | 1 | 1 | 1 | 1 | 1 | 2 | 2 | 2 | 1.20 | 0.4 | 0.20 | 0.80 | |
| | Naples Hits | 0 | 2 | 1 | 1 | 0 | 1 | 1 | 1 | 0 | 1 | 0.80 | 0.62 | 0.25 | 0.87 | |
| 57 | 39.75N/12.75E | | | | | | | | | | | | | | | 0.78 |
| | Rome Hits | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.10 | 0.1 | 0.10 | 0.98 | |
| | Naples Hits | 3 | 3 | 2 | 4 | 2 | 2 | 2 | 2 | 3 | 2 | 2.50 | 0.5 | 0.22 | 0.58 | |

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# APPENDIX B

## RESULTS OF MONTE CARLO TRIALS OF PREFERRED SHIP POSITIONS

| POS | | TBM HITS ON CITIES (BY TRIAL NUMBER) | | | | | | | | | | EXP VAL | VAR | STD ERROR OF EST EXP VAL | Pr( INDIV TBM KILL) | INTEGRATION TBM KILL) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | | | | | |
| 58 | 39.75N/12.25E | | | | | | | | | | | | | | | |
| | Rome Hits | 1 | 1 | 1 | 1 | 2 | 1 | 2 | 1 | 2 | 2 | 1.40 | 0.27 | 0.16 | 0.77 | 0.88 |
| | Naples Hits | 3 | 2 | 2 | 2 | 2 | 3 | 2 | 2 | 3 | 3 | 2.40 | 0.27 | 0.16 | 0.60 | |
| 59 | 40.5N/14E | | | | | | | | | | | | | | | . |
| | Rome Hits | 0 | 0 | 0 | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 0.40 | 0.27 | 0.16 | 0.93 | 0.94 |
| | Naples Hits | 0 | 1 | 1 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0.30 | 0.23 | 0.15 | 0.95 | |
| 60 | 40.5N/14.5E | | | | | | | | | | | | | | | |
| | Rome Hits | 0 | 1 | 0 | 2 | 0 | 0 | 1 | 0 | 0 | 1 | 0.50 | 0.5 | 0.22 | 0.92 | 0.93 |
| | Naples Hits | 0 | 1 | 0 | 0 | 1 | 0 | 0 | 0 | 1 | 0 | 0.30 | 0.23 | 0.15 | 0.95 | |

# APPENDIX C

## CALCULATION OF TBM HIT PROBABILITIES

| POS | Pr(TBM HIT) | | Pr(Zero | Pr(One | Pr(Two | Pr(Two or fewer |
|-----|-------------|--------|------------|-----------|------------|-----------------|
|     | Rome | Naples | TBM hits) | TBM hit) | TBM hits) | TBM hits) |
| 4 | 0.03 | 0.08 | 0.51 | 0.36 | 0.06 | 0.92 |
| 5 | 0.28 | 0.20 | 0.04 | 0.14 | 0.15 | 0.33 |
| 9 | 0.05 | 0.05 | 0.54 | 0.34 | 0.06 | 0.94 |
| 10 | 0.05 | 0.05 | 0.54 | 0.34 | 0.06 | 0.94 |
| 11 | 0.22 | 0.22 | 0.05 | 0.17 | 0.17 | 0.39 |
| 12 | 0.25 | 0.25 | 0.03 | 0.13 | 0.15 | 0.31 |
| 13 | 0.30 | 0.13 | 0.05 | 0.18 | 0.15 | 0.38 |
| 14 | 0.53 | 0.53 | 0.00 | 0.00 | 0.01 | 0.01 |
| 15 | 0.23 | 0.23 | 0.04 | 0.16 | 0.16 | 0.36 |
| 17 | 0.03 | 0.03 | 0.69 | 0.26 | 0.03 | 0.98 |
| 19 | 0.07 | 0.07 | 0.42 | 0.38 | 0.10 | 0.90 |
| 20 | 0.07 | 0.07 | 0.42 | 0.38 | 0.10 | 0.90 |
| 21 | 0.22 | 0.22 | 0.05 | 0.17 | 0.17 | 0.39 |
| 22 | 0.22 | 0.22 | 0.05 | 0.17 | 0.17 | 0.39 |
| 23 | 0.38 | 0.38 | 0.00 | 0.02 | 0.05 | 0.08 |
| 24 | 0.38 | 0.38 | 0.00 | 0.02 | 0.05 | 0.08 |
| 25 | 0.28 | 0.28 | 0.02 | 0.09 | 0.12 | 0.23 |
| 26 | 0.27 | 0.27 | 0.02 | 0.10 | 0.13 | 0.26 |
| 29 | 0.52 | 0.52 | 0.00 | 0.00 | 0.01 | 0.01 |
| 30 | 0.37 | 0.37 | 0.00 | 0.03 | 0.06 | 0.09 |
| 31 | 0.07 | 0.07 | 0.42 | 0.38 | 0.10 | 0.90 |
| 33 | 0.52 | 0.52 | 0.00 | 0.00 | 0.01 | 0.01 |
| 35 | 0.45 | 0.45 | 0.00 | 0.01 | 0.02 | 0.03 |
| 39 | 0.07 | 0.07 | 0.42 | 0.38 | 0.10 | 0.90 |
| 40 | 0.12 | 0.12 | 0.22 | 0.35 | 0.17 | 0.74 |
| 51 | 0.38 | 0.38 | 0.00 | 0.02 | 0.05 | 0.08 |
| 54 | 0.05 | 0.05 | 0.54 | 0.34 | 0.06 | 0.94 |
| 55 | 0.05 | 0.05 | 0.54 | 0.34 | 0.06 | 0.94 |
| 56 | 0.13 | 0.13 | 0.19 | 0.34 | 0.18 | 0.70 |
| 57 | 0.42 | 0.42 | 0.00 | 0.01 | 0.03 | 0.05 |
| 58 | 0.40 | 0.4 | 0.00 | 0.02 | 0.04 | 0.06 |
| 59 | 0.05 | 0.05 | 0.54 | 0.34 | 0.06 | 0.94 |
| 60 | 0.05 | 0.05 | 0.54 | 0.34 | 0.06 | 0.94 |

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